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CONTROLLED ATMOSPHERIC BREAKDOWN
Applications and Research Opportunities

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Directorate of Geophysics
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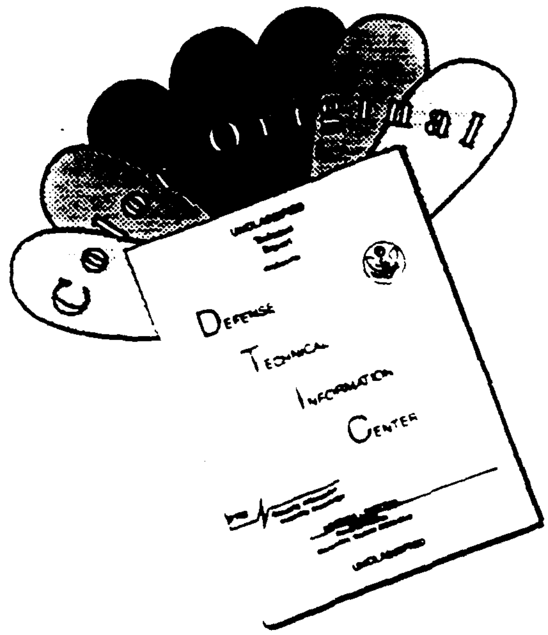

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This document introduces applications and research opportunities associated with the controlled breakdown (i.e., ionization) of selected regions of the atmosphere. United States Air Force interest in this area originated in 1986 under Project Forecast II, a far-reaching effort to exploit revolutionary technologies for enhancing the Air Force's Mission capabilities into the 21 st Century. One such technology identified was the so-called Artificial Ionospheric Mirror (AIM), a concept to employ a ground-based, very high power, microwave transmitter to create localized patches of ionization ("mirrors") in the atmosphere, which could be used as reflectors of radar signal for over-the-horizon surveillance. In the course of research to assess the viability of the AIM concept, interactions with a variety of DoD and civilian agencies, as well as with scientists from various disciplines, have made the prospective benefits of such research clear. There is growing consensus that development of an experiment research facility to produce controlled breakdown of the atmosphere would provide many unique research opportunities and some potentially revolutionary applications. This short report summarizes some of these that key organizations and interested scientists have suggested.

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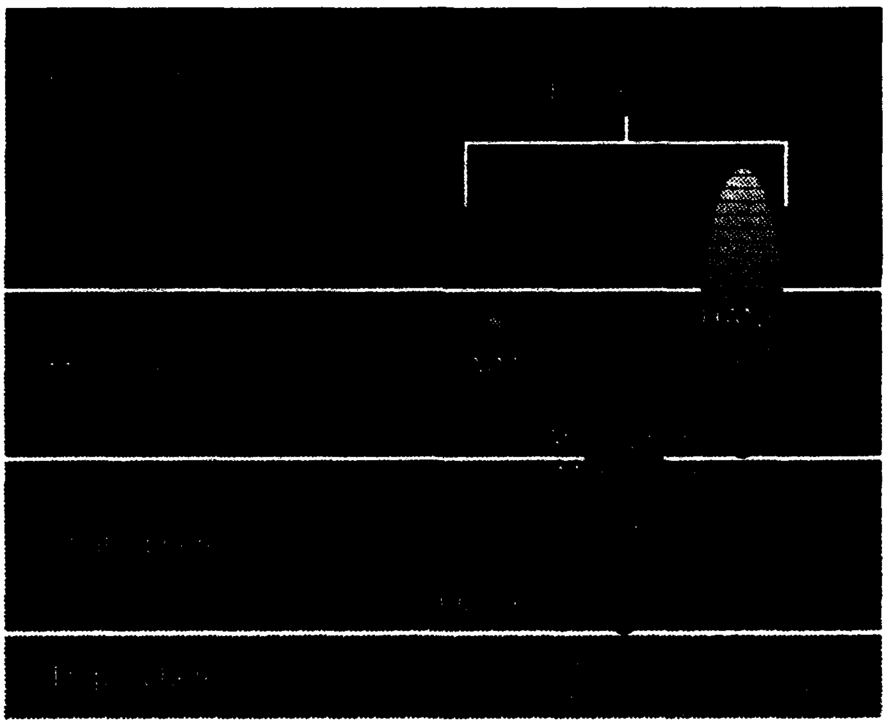

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CONTROLLED ATMOSPHERIC BREAKDOWN

Applications and Research Opportunities

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CONTROLLED ATMOSPHERIC BREAKDOWN
Applications and Research Opportunities

This document introduces research opportunities and applications associated with the controlled breakdown (i.e., ionization) of selected regions of the atmosphere. United States Air Force interest in this area originated in 1986 under Project Forecast II, a far-reaching effort to exploit revolutionary technologies for enhancing the Air Force's mission capabilities into the 21st century.

One such technology identified was the so-called Artificial Ionospheric Mirror (AIM). The AIM concept employs a ground-based, very high power, microwave transmitter to create localized patches of ionization ("mirrors") in the atmosphere, which can be used as reflectors of radar signals for over-the-horizon surveillance. This concept is revolutionary in that it goes beyond limitations imposed on conventional systems by the natural ionosphere. Instead, it envisions seizing direct control of the propagation environment and re-shaping it to ensure that radio wave reflection properties required to achieve a desired surveillance capability are present. Phillips Laboratory's AIM research has focused primarily on assessing the technical viability of the concept for reliable detection of cruise missiles and other low observables. A brief recap of this research is described in the Executive Summary and Chapter 5, AIMS-LO Radar, of this report.

In the course of the AIMS-LO research, interactions with a variety of DOD and civilian agencies, as well as with scientists from various disciplines, have made the prospective benefits of this research clear. There is a growing concensus that development of an experimental research facility to produce controlled breakdown of the atmosphere would provide many unique research opportunities and some potentially revolutionary applications. Because the Phillips Laboratory efforts have focused on just one of these applications, AIMS-LO, this short report is offered to outline some of the others that key organizations and concerned scientists have suggested.

The title page illustration shows altitude regimes for three potential applications of controlled atmospheric breakdown: (1) artificial ionospheric mirror (AIM) for reflecting radio waves; (2) atmospheric monitoring and environmental applications; and (3) non-nuclear simulation of high altitude nuclear effects (HANE) on surveillance systems.

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EXECUTIVE SUMMARY

1. INTRODUCTION

An atmospheric breakdown facility will provide the United States scientific and defense communities with a laboratory-in-the-sky to perform atmospheric and ionospheric research that would otherwise be impossible. In addition to advancing basic research in these two important areas, such a facility will provide critical data for development of innovative surveillance and communication systems and aid in crucial environmental monitoring. The potential reward and scope of application is so great--possibly to the point of revolutionizing selected areas of RF propagation and remote sensing--that continued study of artificial ionization processes is warranted. Furthermore, such a capability will vastly improve upon theoretical studies and small-scale laboratory chamber simulations which are reaching the point of diminishing returns.

Because recent technological advances have removed obstacles to feasibility, it is now possible to proceed with a ground-based facility that can produce and control breakdown and ionization over a range of heights in the atmosphere and lower ionosphere. The National Oceanic and Atmospheric Administration and the Defense Nuclear Agency (DNA), among others, have endorsed this concept, and furthermore, have expressed interest in employing the completed facility. Moreover, the concept has been fully scrutinized in numerous multi-agency symposia sponsored by the United States Air Force.

The following paragraphs describe the facility and discuss five separate applications.

2. THE BREAKDOWN FACILITY

A breakdown facility consists of a large, ground-based, microwave transmitter and a suite of electromagnetic and optical diagnostic sensors. The role of the large transmitter is to break down a patch of air at selected heights between 30- and 100-kilometers, thereby producing ionization and airglow. The ionization can bend or reflect electromagnetic waves and act as a mirror in the sky. The diagnostic sensors will monitor the electromagnetic and optical properties of the breakdown patch. Although several, so-called ionospheric heaters have been operated successfully over the past two decades, none has heretofore been powerful enough to produce breakdown. The goal is to control the breakdown for scientific, military, and/or environmental purposes.

The breakdown transmitter will be a large antenna array, perhaps 1000 meters in diameter. That array will be a dilute one whose elements are sparsely distributed. Power requirements are high but feasible. Peak powers may be one- to a few-hundred megawatts, whereas average powers will be a few megawatts. Such powers can be achieved with reasonable numbers of high-power klystrons, for example. Even more powerful high-power-microwave devices will evolve over the next few years. Analyses show that environmental impacts are short-lived and can be controlled to conform to acceptable limits.

3. BASIC ATMOSPHERIC RESEARCH

The breakdown facility will, for the first time, allow sustained and repetitive measurements of the upper stratosphere, the mesosphere, and the lower thermosphere and the ionosphere. Those atmospheric regions have been inaccessible to such measurement in the past because they are too high for balloon-borne instruments and too low for instruments on earth-orbiting satellites. Moreover, theoretical studies and small scale laboratory chamber simulations are reaching the point of diminishing returns. The breakdown facility will probe the atmosphere at heights chosen for a specific scientific purpose without the contamination from chamber walls that often adversely affects laboratory chamber experiments.

The diagnostic capability of the breakdown facility will be robust, and only depends upon creating a patch that glows brightly enough to be sensed and tracked through telescopes located on the ground, on aircraft, or in space. The following scientific goals can be accomplished:

- Perform ozone photochemistry;
- Identify and track trace elements;
- Provide database on winds, waves, temperature, and tides;
- Infer electric fields and their dependence on solar winds;
- Provide data to evaluate aerobraking;
- Create and evaluate artificial "mini-auroras;"
- Evaluate how the mesosphere couples the stratosphere to the ionosphere/ thermosphere;
- Investigate atmospheric gravity waves.

4. ENVIRONMENTAL AND GLOBAL CHANGE APPLICATIONS

Despite their small concentrations, certain trace elements influence the chemistry and energetics of the stratosphere and mesosphere. Anthropogenic changes in those trace elements over the next two decades are expected to alter the environment. It is important to monitor the concentrations of such trace elements as well as their transport via diffusion and atmospheric winds. As with the use of a breakdown facility to produce airglow and employ emission spectroscopy to monitor trace elements, the same principles apply to the monitoring and modeling of processes, such as ozone photochemistry, that lead to global change.

5. AIMS-LO (Artificial Ionospheric Mirror for Surveillance of Low Observables) RADAR

The AIMS-LO radar concept envisions a powerful, ground-based, radio-wave transmitter to create and control patches of ionization in the atmosphere at heights around 70 or 80 kilometers. Such ionized patches can reflect electromagnetic signals back toward earth and therefore act as an artificial "mirror" to reflect over-the-horizon (OTH) radar signals. The AIMS-LO concept is revolutionary because it will seize control of the ionosphere and re-shape it to create capabilities not possible with conventional OTH radars that are constrained by the limitations and vagaries of the natural ionosphere. Among those capabilities are:

- Optimum detection of small, low-observable targets, including cruise missiles;
- Avoidance of auroral degradation in Northern latitudes;
- Single-site, 360 degree coverage of theaters or cities;
- Detecting and locating mobile-missile launches, like SCUD;
- Suppression of sea clutter, thereby greatly enhancing radar performance over oceans.
- Filling the 100-to-1200 kilometer range gap between conventional line-of-sight (LOS) radars and OTH radars;

The Air Force Geophysics Laboratory (now Phillips Laboratory) initiated research on AIMS-LO in 1987 with support from the Air Force's Electronic Systems Division. In 1989 the blue-ribbon JASON panel reviewed the research results produced by multiple organizations and found no basic physics issues which preclude realization of AIMS-LO. An experimental breakdown facility is a logical step toward a full-fledged AIMS-LO.

6. RELIABLE COMMUNICATION LINKS

The breakdown facility will answer many questions regarding production of an artificial ionospheric mirror. Such a mirror acts like a directable, passive, low-altitude communications satellite that can (1) reflect very-short-wave signals that ordinarily would pass uselessly through the ionosphere and into space; (2) be located and oriented to direct signals toward specified regions; and (3) reflect signals below the normal ionosphere, thereby avoiding degradation from ionospheric fluctuations. An artificial ionospheric mirror might therefore be used to provide reliable communications links free from the vagaries of the ionosphere, especially at auroral latitudes.

7. NON-NUCLEAR SIMULATION AND MODELING OF HIGH-ALTITUDE NUCLEAR EFFECTS (HANE) ON SURVEILLANCE SYSTEMS

Although dissolution of the Soviet Union has greatly reduced the chance that high altitude nuclear detonations will ever occur, it is worth noting that a breakdown facility has a capability for non-nuclear simulation of nuclear events. It is beyond the scope of this paper to assess the future likelihood of high altitude nuclear explosions (HANE); nonetheless, outlining the potential benefits of a breakdown facility in this regard should prove instructive to any interested reader.

A nuclear detonation ionizes and excites air molecules over a huge volume, and those molecules radiate strongly in optical bands. That radiation can damage or overwhelm optical and infrared surveillance and tracking systems. The ionized volume also absorbs electromagnetic waves and degrades radio communication or radar systems. The simulation of certain effects of a high altitude nuclear explosion on planned or existing military systems can be an added advantage of an atmospheric breakdown facility.

In the past, absence of atmospheric nuclear testing has confined simulation of the nuclear environment to the laboratory by use of large vacuum ionization chambers with sophisticated radiation sources and diagnostic devices. Many useful results have been obtained, but questions were raised by unwanted effects caused by chamber walls. Non-confined atmospheric experiments have included ground-, rocket-, and satellite-based measurements during auroras, strong solar flares, and solar proton events, all of which vaguely mimic certain atmospheric effects of high-altitude nuclear explosions. Although useful, those data were limited because the energy deposited in the atmosphere during natural events is uncontrolled and therefore poorly understood, and is orders of magnitude less intense than the energy deposited by a nuclear weapon. A breakdown facility eliminates these shortcomings: there are no chamber walls, the energy deposited is controlled, and it is very intense.

A breakdown facility can create airglow that would help to understand and mitigate nuclear-weapons induced emissions that interfere with optical detection and tracking of missiles and re-entry vehicles. Indeed, it can be used to calibrate the sensitivity of U.S. surveillance systems against realistic backgrounds.

8. RESEARCH IN THE FORMER SOVIET UNION AND COLLABORATION WITH COMMONWEALTH OF INDEPENDENT STATES (CIS)

Scientists from the former Soviet Union have conducted an orderly and innovative research program on atmospheric breakdown. The concept of using dual, intersecting, high-power microwave beams to define and sustain an ionized region originated in the Soviet Union. Achieving steady progress over the past decade, they have developed a well-defined recommendation for a prototype facility using a multiple-pulse, intersecting beam method of ionizing the neutral atmosphere. That approach, leading to artificially ionized radio reflectors, has been described in the Soviet and CIS literature as offering new paths for a wide variety of civilian and military radio frequency (RF) applications, including enhanced long-range communications and avoidance of disturbed environments. Opportunities for cooperative basic scientific research with the CIS in this area appear realistic, since a joint symposium on artificial ionization research has recently been held, and several high-level inquiries from the CIS have already been made.

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Section 1
INTRODUCTION

An atmospheric breakdown facility will provide the United States scientific and defense communities with a laboratory-in-the-sky to perform atmospheric and ionospheric experiments that would otherwise be impossible. In addition to advancing basic research in these two important areas, such a facility will provide critical data for development of surveillance and communication systems that can operate under most atmospheric conditions, and aid in crucial environmental monitoring. Furthermore, theoretical studies and small scale laboratory chamber simulations of atmospheric breakdown are reaching the point of diminishing returns. The potential reward and scope of application is so great--possibly to the point of revolutionizing selected areas of RF propagation and remote sensing--that continued study of artificial ionization processes is warranted.

Technological advances in such areas as high-power microwave (HPM) sources and digital control of large computer arrays have removed obstacles to the feasibility of a breakdown facility. It is therefore now possible to proceed with a ground-based facility that can produce and control breakdown and ionization over a range of heights in the atmosphere and lower ionosphere. For the above reasons, a number of organizations, including the National Oceanic and Atmospheric Administration and the DNA, have endorsed the concept and expressed interest in using the completed facility.

A breakdown facility consists of a large, ground-based microwave transmitter, herein called a controlled atmospheric breakdown (CAB) array, and a suite of electromagnetic and optical diagnostic sensors. The role of the CAB array is to break down a patch of air at selected heights between 30- and 100-kilometers, thereby producing ionization and airglow. The auxiliary sensors will monitor the electromagnetic and optical properties of the patch. Although several ionospheric *heating* arrays have been operated successfully over the past two decades, none has heretofore been powerful enough to produce breakdown.

The breakdown facility will, for the first time, allow sustained and repetitive measurements of the upper stratosphere, the mesosphere, and the lower thermosphere and ionosphere. Those atmospheric regions have been inaccessible to such measurement because they are too high for balloon-borne instruments and too low for instruments on earth orbiting satellites. The breakdown facility will probe the atmosphere at heights chosen for specific scientific purposes without the contamination from chamber walls that often adversely affects laboratory experiments.

The feasibility of a breakdown facility has been brought forth in extensive studies carried out in the United States and the former Soviet Union, and a book, <u>Artificial Ionized Region in the Atmosphere</u> by N. Borisov, A. Gurevich and G. Milikh [Moscow, 1986], has been written on the subject. The U.S., blue-ribbon JASON panel found no insurmountable technological obstacles to a breakdown facility at least as ambitious as the one discussed here. Moreover, the concept has been fully scrutinized in numerous symposia sponsored by the United States Air Force.

Section 2 of this paper describes how a ground-based facility can produce controlled breakdown high in the atmosphere. In Sec. 3 basic atmospheric research that the facility will perform is summarized. Suggestions for opportunities to use a breakdown facility for environmental and global change applications are offered in Sec. 4. Section 5 describes the AIMS-LO radar, an innovative concept for detecting low-observable targets that is based on the ability to produce and control atmospheric breakdown. Section 6 describes special communications applications that might be possible with controlled breakdown. A breakdown facility will contribute to the understanding and mitigation of high-altitude nuclear weapons effects on surveillance systems, and that issue is addressed in Sec. 7. In conclusion, Sec. 8 summarizes areas of possible collaboration on basic research with scientists from the Commonwealth of Independent States (CIS).

Section 2
AN ATMOSPHERIC BREAKDOWN FACILITY

A breakdown facility will provide an open laboratory previously unavailable to atmospheric scientists. Such a facility will have many uses, including: basic atmospheric research, environmental monitoring, and proof-of principles experiments for future military systems. This section describes salient aspects of atmospheric breakdown and indicates alternative types of facilities.

ATMOSPHERIC BREAKDOWN

Breakdown is a process wherein a gas subjected to an intense electromagnetic field becomes "electrified" and assumes certain properties of electrical conductors. Breakdown occurs because atoms and molecules in the air are literally broken down into subsidiary particles. Accompanying the electrification are optical emissions and airglow. Well-known examples of atmospheric breakdown are the luminous channels in which lightning flashes travel, the auroras, and the bluish corona that surrounds high-voltage cables. Controlled air breakdown has been common in the laboratory for decades, and the physical processes are well understood and quantified. The goal is to control atmospheric breakdown outside the laboratory so it can be used for scientific research, environmental monitoring, civilian and/or military applications.

The vast majority of atmospheric constituents are electrically neutral because they contain equal numbers of heavy, positively-charged protons and light, negatively-charged electrons. The protons concentrate in the nucleus of an atom, whereas the electrons orbit the nucleus and are much less tightly bound than the protons. Such neutral particles neither affect nor respond to an electromagnetic field. Under certain conditions, however, electrons undergo collisions with other particles or radiation and are knocked loose from atoms to become free electrons, which can have a profound effect on electromagnetic fields. The residual, positively-charged atoms, or molecules, form ions.

Atmospheric breakdown originates when a strong electric field is imposed on free electrons, which are always present. Such ambient free electrons have been knocked loose by solar or cosmic radiation and are plentiful at altitudes above 60 kilometers; at lower altitudes their number density is tiny, but not zero. An electric field exerts a force on a free electron and causes it to gain speed until it collides with other atmospheric particles and stops. If the electron gains enough speed between collisions, it will knock other electrons loose. These new free electrons are then accelerated by the applied field, and the process repeats with more and more electrons participating. The result is an avalanche, wherein the number of free electrons quickly builds to a huge value.

This avalanche, wherein free electrons beget ever increasing numbers of additional free electrons, does not progress indefinitely, because de-ionization and diffusion deplete the electron density. De-ionization occurs when free electrons combine with positive ions or attach to neutral particles. Diffusion causes clumps of electrons to disperse, much as a puff of smoke disperses throughout a room. Breakdown is therefore self-limiting; it reaches a steady state when de-ionization or diffusion exactly cancels the rate of electron production (ionization) in the avalanche.

The minimum electric field required to produce breakdown is called the "critical field." How strong must that field be? The answer depends on the air density and hence on height above the ground. At low altitudes, where the air is dense and its molecules closely packed, a huge electric field is needed to accelerate an electron to ionizing speed before a collision occurs. At high altitudes, where the air is rarefied and the molecules farther apart, a much weaker field will do the job. For example, the DC electric field required to cause breakdown at a height of 30 kilometers is about a thousandfold stronger than the field required to cause breakdown at a height of 80 kilometers.

Because the breakdown region becomes a conductor of electricity, it will absorb, bend, reflect, or deflect electromagnetic waves. Although such interactions between waves and ionized air are useful for certain applications, they must be accounted for in the design of the facility itself.

The goal is to use a ground-based facility to produce ionization at a specified height in the atmosphere. The way to accomplish that goal is to construct a microwave transmitter that will radiate electromagnetic beams whose strength will exceed the critical field at the desired height. The beam's electric field must not exceed the critical field below the specified height, however, or breakdown along the propagation path will deflect or absorb the beam before it reaches its destination. Such self-limitation must be avoided. That task is made easier because, as stated, the critical field becomes smaller as the height increases. Unfortunately, there is a compensating effect: beams radiated from conventional antennas diverge and are strongest near the antennas. A non-conventional approach therefore is needed.

TWO CONCEPTS FOR A BREAKDOWN FACILITY

Although the preferred configuration for a breakdown facility must await final design, there are two generic choices: crossed beam and focused beam. Both choices allow control of where in the atmosphere the breakdown occurs.

Crossed Beam

The crossed beam approach was pioneered in the former Soviet Union, and many papers on the subject have appeared in Soviet scientific journals since the late 1970s. Figure 1 illustrates this approach for the simplest case where only two beams are used, but the discussion applies to any number of beams. Instead of using a single, powerful beam, which would cause unwanted breakdown below the desired altitude, a crossed-

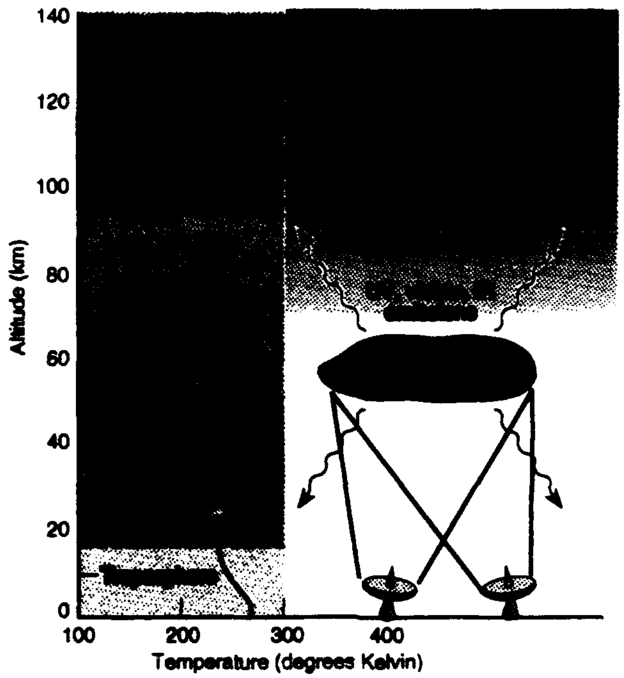

Figure 1. Diagram of multi-beam breakdown facility. Also shown are nominal locations of atmospheric layers.

beam facility would use multiple beams, each of which is too weak to cause breakdown along its path. In the region where the beams intersect, however, the fields from the individual beams add up to a total field that exceeds the critical field. Breakdown is therefore produced only in the intersection region, the height and location of which can be controlled by adjusting the width and launch angles of the individual beams. Theoretical work and laboratory chamber measurements in the Soviet Union and the United States indicate that the crossed beam approach will work in the atmosphere.

Figure 1 also shows the main layers of the atmosphere, and plots temperature versus height. The locations of the layers shown are nominal and vary with atmospheric conditions, especially temperature. The ionosphere is an ionized layer that surrounds earth, partially overlapping the mesosphere and thermosphere. It is the ionosphere that reflects radio waves back toward earth and makes possible radio communication beyond the earth's horizon without using earth satellites. The figure shows the breakdown region to be located in the mesosphere, below the normal ionosphere. Although such heights are good ones for breakdown experiments, other heights can be achieved by adjusting beam parameters.

Focused Beam

The focused beam approach has been analyzed theoretically and numerically in the United States and has many attractive features. As opposed to conventional antennas, the beam from a focused antenna actually grows stronger as the distance increases and reaches a maximum at a distance equal to the focal length. That phenomena is analogous to the familiar behavior of sunlight shining through a magnifying glass. A piece of paper placed at the focal length, where the beam is narrowest and most intense, will ignite. Placement at shorter or greater distances will cause no such ignition. A focused beam breakdown facility will adjust the focal length to coincide with the desired breakdown region. Breakdown will not occur at lower altitudes because the beam is weaker there. Figure 2 shows an example where the array diameter is large, perhaps a thousand times greater than the length of the electromagnetic waves that comprise the beam. For a wavelength of 1 meter, a reasonable value, the array might be about a kilometer across and composed of many elements. Such large diameter arrays are necessary for focusing at distances of many tens of kilometers. Smaller arrays have focal lengths too short to be useful for an atmospheric breakdown facility.

One disadvantage of the focused beam approach is that the diameter of the hot-spot might not be large enough for certain applications. That diameter can be increased by de-focusing the beam, but such de-focusing reduces the beam intensity and the radiated power must be increased proportionally. Such power increases are undesirable, and might even be unfeasible. A feasible approach to this problem lies in a process called "painting," which is illustrated in Fig. 2.

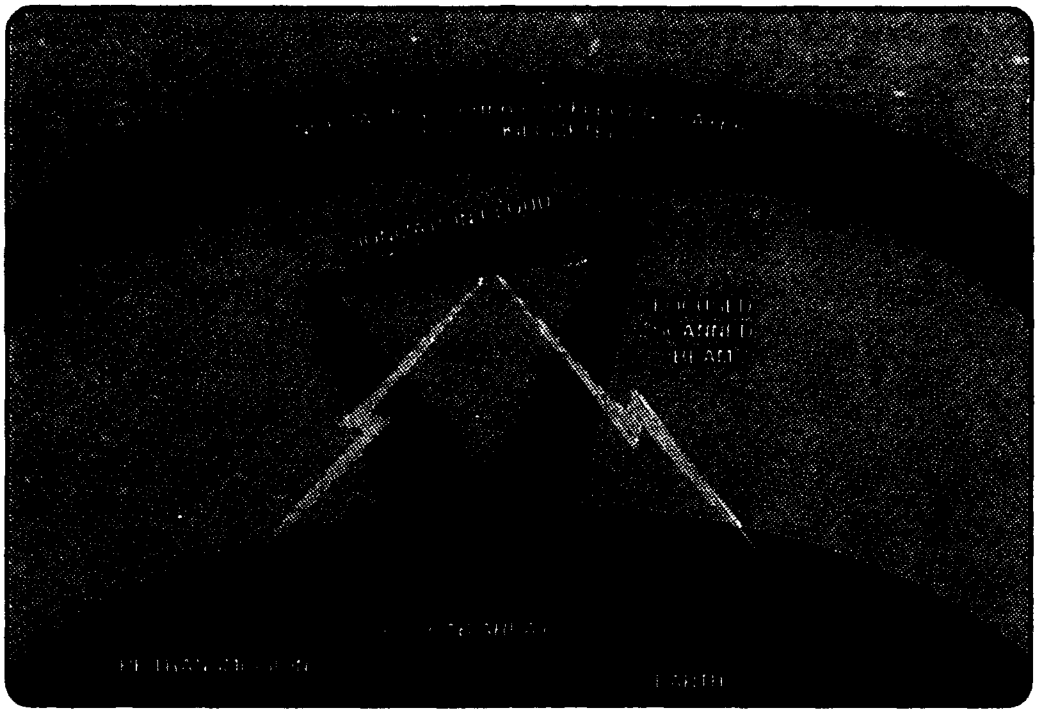

Figure 2. Diagram of focused-beam breakdown facility that produces a large ionization cloud by scanning ("painting") the focused spot. Also shown is a radio wave being reflected by the ionized cloud.

Painting capitalizes on the fact that ionization, once produced, tends to persist until depleted by de-ionization or diffusion. The persistence time depends on many factors, but it is often long enough (a substantial fraction of a second) to allow the antenna beam to be steered from the initial ionized region in order to produce breakdown in additional regions and then be swung back to re-establish ionization in the first region. By taking advantage of such beam-scanning, or painting, a focused beam breakdown facility can build up a sizable ionized region from many small hot spots.

POWER REQUIREMENTS AND AVAILABLE HIGH-POWER SOURCES

How much power might be required for a breakdown facility? A definitive answer cannot be given until preliminary design has been completed because trade-offs exist among wavelength, antenna size, and power. In any event, power requirements are high.

For example, the *peak* power--that is, the power while the transmitter is on--could be on the order of one hundred million watts for an antenna array a thousand meters or so in diameter. The average power is much lower; the transmitter might have to be on for only 1-to-10 percent of the time because, as mentioned, the breakdown persists and does not have to be excited continuously. The *average* power could therefore lie between one megawatt and ten megawatts, depending on the circumstances.

Although such powers are high, technological advances indicate that adequate sources of power will be available. It is important to recognize that a single source need not supply all the power. An array containing many tens--or even hundreds-- of separate elements is satisfactory. Moreover, there is no need to construct a single, huge antenna a kilometer or more in diameter. A dilute array whose elements are sparsely distributed over the array area will work.

Figure 3 plots peak and average power domains for microwave sources as of 1991. The portion of the figure labeled "conventional microwave" sources pertains to magnetrons and klystrons, which have been evolving since the 1940s. The portion of the figure labeled HPM (high-power microwave) pertains to newer devices described in the recent High Power Microwaves by J. Benford and J. Swegle [Astech House, 1991]. These HPM devices deliver huge peak power but only low average power because they have been designed for single-pulse applications rather than continuous or repetitive operations. The impetus provided by new applications is expected to spur advances in repetitive operation, with average power levels of 100 kilowatts to be achieved in a few years.

As an example, consider a CAB array that operates at 300 MHz and has a diameter of 1000 meters. Analysis shows that a peak power of a few hundred megawatts and an average power of a few megawatts is needed, depending on certain other

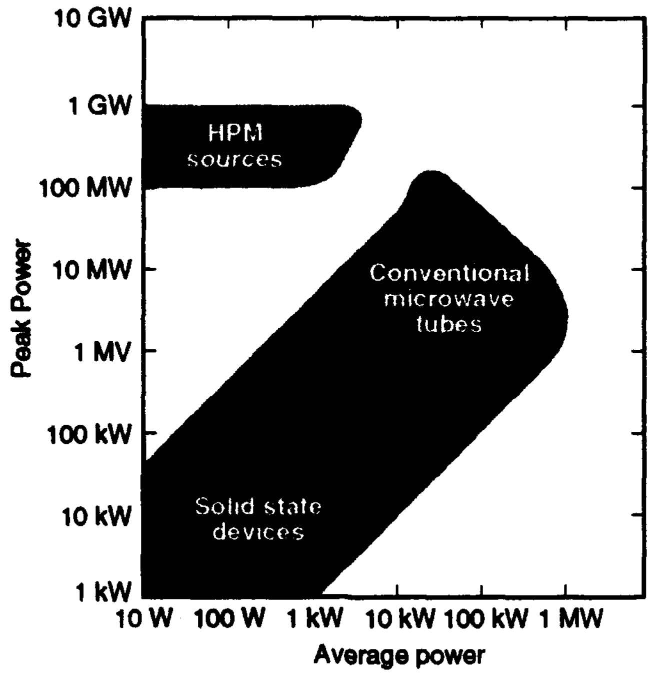

Figure 3. Peak powers and average powers for microwave devices in 1991 [from High-Power Microwave Sources by J. Benford and J. Swegle].

parameters. Those powers could be delivered by, say, 30 conventional microwave tubes. Fewer HPM sources would be needed if the average power for such devices is improved, as predicted, over the next few years.

DIAGNOSTICS

In order to measure the properties of the atmosphere in the breakdown region, a number of auxiliary sensors must be deployed in addition to the breakdown facility itself. Otherwise, little or no information could be gleaned from experiments. A detailed list of such diagnostic sensors must await decisions on which experiments are to be performed. Subsequent sections indicate which measurements are needed for specific purposes.

There are two generic phenomena on which diagnostics can be based: electromagnetic scattering and optical emissions. Below are some general observations on each type.

As mentioned above, the region ionized by breakdown becomes electrically conductive and can reflect upward traveling radio waves down towards the earth or scatter such signals over many directions. Radars and radio sounders therefore are expected to be primary diagnostic tools for determining the reflective or scattering properties of the breakdown regions. Moreover, ground-based backscatter radars can measure the temperature and structure of an ionized cloud, even though that cloud will be located many miles above the earth's surface. Figure 2 illustrates a generic, ground-based RF transmitter for use in scattering electromagnetic energy off of the breakdown cloud.

The breakdown region will emit optical energy with wavelengths in the infrared, visible light, and ultraviolet portions of the spectrum. Such emissions--illustrated in Fig. 1--comprise an airglow.

Figure 4 shows a false-color presentation of airglow produced about 330 kilometers above the Arecibo High Frequency (HF) facility in Puerto Rico. That transmitter was operated at a much lower effective power and radio frequency (about 3 MHz) than envisioned for the CAB array. The actual color of the airglow was red, which corresponds to an emission line of oxygen atoms; the brightest colors in the presentation represent the regions where the red emissions were strongest. Far too weak to be seen by the naked eye, the image shown was detected with an intensified charge-coupled device camera.

The airglow patch is influenced by the geomagnetic field, the radiation pattern of the radio beam, the ambient geoelectric field, ionospheric winds, and ionospheric particle densities. Images of the airglow patch can give information on these properties, as well as on the efficiency with which the facility produced the patch. For example, the cloud shown in Fig. 4 was observed to be many tens of kilometers in extent and to drift westward at a speed of about 70 meters per second.

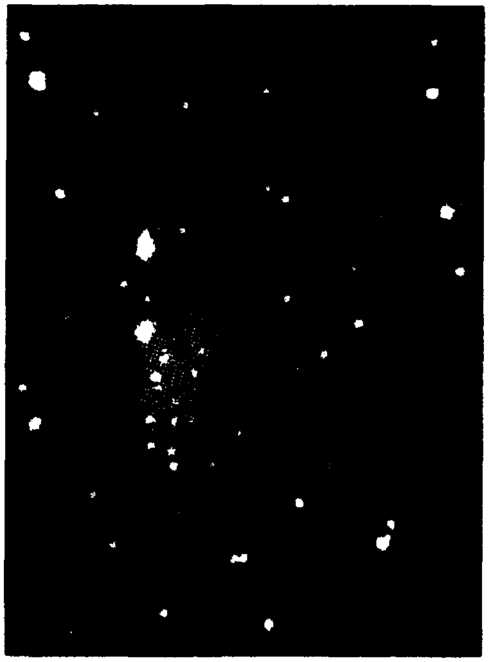

Figure 4. False-color presentation of red airglow from oxygen atoms excited by 3 MHz transmissions from the HF facility at Arecibo, Puerto Rico. The various colors shown indicate different intensities of the red emissions, with yellow indicating the most intense. [Courtesy Naval Research Laboratory.]

Because the controlled breakdown facility will have much greater effective power than Arecibo and will operate at much higher frequencies, the resulting airglow patch will differ in many respects from the one shown. Specifically, it will (1) be much brighter; (2) contain a wider variety of emissions and hence yield information on species in addition to atomic oxygen; (3) occur at lower altitudes; and (4) be more controllable and sharply defined. For those reasons, patches caused by the CAB array will be much more versatile as diagnostic tools than the one shown.

The many species (atoms and molecules) that comprise the cloud can be identified passively by using spectroscopy to separate the emissions into component colors and associate each specie with its characteristic emission color. Active probing of the cloud can be accomplished with lidars. The required optical measurements can be made with instruments based on the ground (as for Fig. 4), aircraft, or earth satellites.

ENVIRONMENTAL IMPACT OF AN ATMOSPHERIC BREAKDOWN FACILITY

An atmospheric breakdown facility invokes two different types of environmental considerations. First, the facility can be used to detect and monitor important ionospheric species. That application is discussed in Sec. 4. Second, an atmospheric breakdown facility must not have an adverse impact on the environment. This aspect is discussed below.

Most effects of a breakdown facility will be short-lived, with the atmosphere returning quickly to a normal state. Such effects can be controlled and kept below acceptable limits. Lightning, auroras, and corona are examples of natural and man-made atmospheric breakdown that routinely occur with no apparent ill effects.

One possible area of concern is with the very high powers and strong electromagnetic fields that would be created by a breakdown facility. A mitigating factor, though, is that both the crossed-beam and focused-beam approaches produce their strongest fields only in the breakdown region high in the atmosphere; it will be possible to ensure that field strengths near the ground are within approved standards. Nonetheless, care must be exercised so as not to interfere with other facilities that use the same radio frequencies as the breakdown facility. Moreover, the facility must be designed and its transmissions scheduled so as not to expose satellites or other spacecraft to damage as they pass above the CAB array.

It is also important to ensure that the controlled breakdown does not adversely affect the chemistry of the atmosphere. For example, Soviet and U.S. studies have shown that very high ionization rates could produce nitric oxide in the breakdown region. Whether or not such production has deleterious side effects depends on its intensity and the height at which it occurs. Analysis indicates that nitric oxide synthesis in the 70-to-100 kilometer height range is not an environmental concern, even for the intense ionization rates envisioned for the AIMS-LO radar (see Sec. 5).

Research is continuing on any negative environmental impacts and will be completed prior to implementation and operation. It should again be emphasized that all effects caused by the facility will be controlled and short-lived. No substantial or permanent changes to the environment will be permitted.

Section 3
BASIC ATMOSPHERIC RESEARCH

A breakdown facility can enhance our understanding of two important atmospheric regions, the mesosphere and the stratosphere. It will identify and monitor trace elements, explore ozone photochemistry, and determine several basic properties of these regions.

MESOSPHERIC DIAGNOSTICS

Figure 1 showed that the mesosphere extends from about 50 kilometers to 90 kilometers, whereas the stratosphere extends from about 15 kilometers to 50 kilometers. The mesosphere is probably the least explored and understood region of the near-earth space environment. For this reason it has recently been dubbed the "ignosphere."

This scarcity of information on the mesosphere is by no means caused by a lack of interest or low priority. To the contrary, the mesosphere is a key boundary layer, being characterized by complex interplay among winds, chemistry, and radiation. It is the valve that controls the coupling of the electrically conductive ionosphere to the non-conductive stratosphere. An accurate description of the mesosphere is necessary, furthermore, to analyze aerobraking, a key issue for the National Aerospace Plane (NASP) and space shuttle (STS) re-entry. The reason for the "ignosphere" label is that it has proven difficult to gain access to the mesosphere with diagnostic sensors. Balloon-borne instruments, the mainstay of stratospheric measurements, cannot be flown high enough, whereas satellite-borne instruments, invaluable for thermospheric and ionospheric measurements, cannot be flown low enough for extended time periods. It is an exciting prospect that the optimum height range for probing by a ground-based breakdown facility falls squarely within the mesosphere.

ISSUES AND REQUIRED MEASUREMENTS

There are a number of mesospheric properties that have never been measured systematically at any single site--composition and temperature, for example. Data are therefore needed to quantify such properties . Although the major charged-components are known to be free electrons and large ions (clusters), there are no reliable data or models that describe the distributions of those components. This lack of knowledge has led to speculation whether charged aerosols exist in the mesosphere and what their role might be.

A particularly important issue is the mesospheric electric field, whose strength is known to be variable and span many orders of magnitude. An understanding of this field is needed to interpret the electrodynamic coupling of the atmosphere/mesosphere system to the ionosphere. Similarly, measurements of the distribution of mesospheric winds, waves, and tides are important for understanding the coupling between the mesosphere and thermosphere.

The mesosphere is influenced by man-made phenomena, and it is likely that increasing levels of methane and carbon dioxide will produce important changes in its chemistry, composition, and dynamics over the next two decades. Those increased levels can profoundly influence the delicate balance of chemical and dynamic forces. For example, methane is oxidized readily into water vapor, which alters atmospheric chemistry in a way that influences ozone levels and mesospheric heating and temperature. It is important to acquire the data needed to understand and quantify these processes.

The mesosphere contains numerous trace constituents. Some of these trace elements are known, whereas others of potential significance that influence or control important processes might be discovered in the future. Because many of these constituents are extremely rare or reactive, it is difficult or impossible to study them in laboratory chamber simulations; direct atmospheric observations are needed to measure atomic or molecular cross-sections and chemical reaction rates of such trace constituents. A breakdown facility can be used as an open laboratory for studies of atomic and molecular physics and chemistry.

MESOSPHERIC DIAGNOSTIC CONCEPT

During the formation, maintenance, and decay of a breakdown-induced ionized cloud, most of the energy from the array beam (or beams) excites molecules and ion clusters, which then emit optical energy and cause the breakdown cloud to be luminous (see Figs. 1 and 4). The spectral content and time-dependence of these emissions depend on which neutral and ionized species are present in the breakdown region. By monitoring the prompt and afterglow emissions and fluorescence with ground-, balloon-, or space-based telescopes, it is possible to determine the concentrations of the various species. Such a breakdown cloud is well suited for probing by laser beams (lidars), because higher than normal concentrations of excited molecules will be present. By following the motion and decay of the airglow after the CAB array is turned off, it is possible to infer properties of mesospheric winds, electric fields, temperature, and trace constituents.

Another area of interest is the structure of atmospheric gravity waves in the upper mesosphere. Such waves are analogous to the swells that occur on the ocean's surface, but are much more complicated and difficult to define through measurements. A breakdown facility offers promise of experimental investigation of such waves by exciting the thin layer of sodium atoms deposited at the relevant heights by meteorite burn-up. Monitoring of the sodium doublet line thus excited will give data on the horizontal structure of this layer, especially as affected by atmospheric gravity waves generated by thunderstorms.

The diagnostic capabilities of a breakdown facility will be robust, and only dependent upon creating a patch that glows brightly enough to be sensed and tracked remotely. Unlike the radar applications of breakdown discussed in Sec. 5, mesospheric diagnostics do not require the ionized patch to be large, smooth, or specially oriented.

In summary, a controlled, ground-based breakdown facility and associated auxiliary instruments can accomplish the following goals by producing and monitoring airglow in the mesosphere:

- Determine neutral and electrically charged composition;
- Provide database on winds, waves, temperature and tides;
- Infer structure and dynamics of electric fields and their dependence on solar winds;
- Provide data to evaluate aerobraking;
- Explore ozone photochemistry;
- Create and evaluate artificial "mini-auroras;"
- Evaluate role of the mesosphere in coupling the stratosphere to the ionosphere/thermosphere;
- Identify and track trace elements;
- Investigate atmospheric gravity waves.

STRATOSPHERIC SPECTROSCOPY

Because early research on a breakdown stemmed from the concept of creating a radar/radio "mirror" in the 50-to-100 kilometers height range, most interest has centered on the mesosphere. It is, however, feasible to create breakdown in the 20-to-30 kilometer height range, which includes the middle and upper regions of the stratosphere. Such an ionization patch would be too short-lived and too dominated by neutral molecules to be useful for radar/radio applications, but it would be valuable for stratospheric diagnostics.

Although the parameters are different, the approach for stratospheric diagnostics is similar to the one described above for mesospheric diagnostics: either a focused beam or a cross beam array is used to produce breakdown at the desired altitude and the ensuing emissions are monitored and analyzed by ground-based photometers, infrared receivers, and microwave receivers. The strength of the spectral lines from the afterglow provides continuous information on the concentrations and dynamics of minority species, including ozone and chlorine.

One difference between stratospheric and mesospheric diagnostics is that the atmosphere is much denser in the stratosphere, so the ratio of free electrons to ambient molecules in the breakdown region is infinitesimal, and the technique is non-perturbing. Notwithstanding that a stronger electric field must be delivered to the stratosphere than the mesosphere in order to produce breakdown, as pointed out in Sec. 2, it is still easier to produce breakdown in the stratosphere because the beam need not travel as far from array to breakdown region.

Section 4
ENVIRONMENTAL AND GLOBAL CHANGE APPLICATIONS

An atmospheric breakdown facility can detect and monitor trace elements that, despite their small concentrations, strongly influence the chemistry and energetics of the stratosphere and mesosphere. Anthropogenic changes in those trace elements over the next two decades are expected to alter the environment. Among the many processes that are controlled by minority constituents are the following:

- Global warming related to atmospheric loading of reactive minority species, such as chlorine;
- Contribution of nitric oxide to the cooling of the lower thermosphere through its emission of infrared radiation;
- Catalytic action of nitric oxide and other nitrogen-oxygen compounds that increase the rate at which ozone and atomic oxygen combine, thereby forming molecular oxygen while removing ozone from the atmosphere;
- Cooling of the mesosphere by increased amounts of carbon dioxide, allowing ice clouds (polar mesospheric clouds) to form at lower latitudes than at present;
- Atomic oxygenation (as opposed to the more common molecular oxygenation) which facilitates mesospheric cooling;
- Methane increases at 1-to-2 percent per year in the middle atmosphere and, with its subsequent oxidation to water vapor, probably results in more polar mesospheric cloud formation and a decrease in ozone concentration.

Accurate modeling requires continuous modeling of the abundance of controlling minority species as well as their transport via diffusion and atmospheric winds.

Emission spectroscopy is a proven method for detecting trace elements. The use of a breakdown facility to produce emissions and allow emission spectroscopy to monitor the abundance and transport of trace elements was discussed in Sec. 3. The same principles apply to the monitoring and modeling of processes that lead to global change. For example, Fig. 5 shows schematically how active (lidar) and passive (spectroscope) methods can be used in conjunction with the breakdown facility to monitor trace species that could affect the ozone layer.

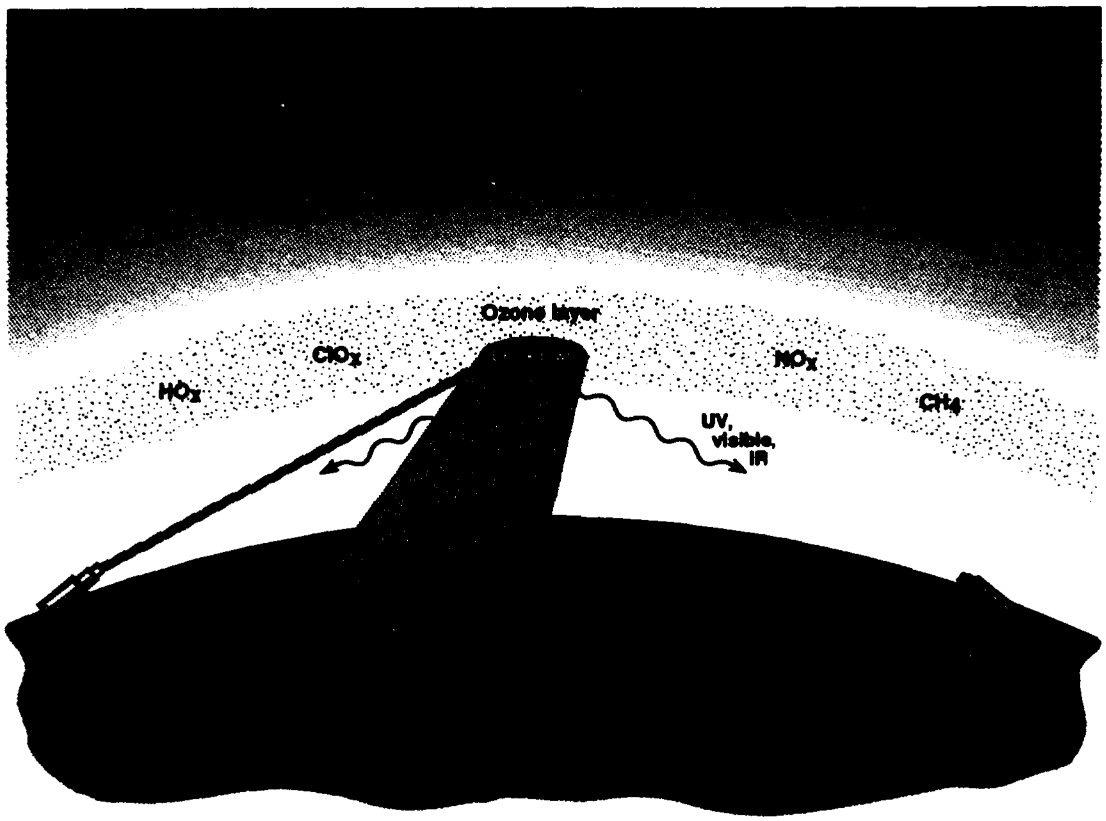

Figure 5. Active and passive identification and tracking of ozone-layer constituents by monitoring emissions induced by breakdown facility.

It is important, however, to make a distinction between *detecting* naturally occurring trace elements versus actually *producing* or *depleting* such elements. The difference lies in the amount and rate of energy deposition. For detection and monitoring, the energy density in the array beam must be large enough to produce detectable airglow, but not so large as to create (or deplete) an amount of the trace species comparable with the concentration that is present initially. Clearly, substantial alteration of the trace element population should *not* be attempted with the breakdown facility until and unless it is demonstrated convincingly that such alteration would have beneficial effects--for example, replenishing ozone. Because more research is needed on that subject, the facility will be operated only at levels needed to detect and monitor trace elements without substantially distorting the ambient populations.

Section 5
AIMS-LO RADAR

The AIMS-LO radar concept envisions use of a powerful, ground-based, radio-wave transmitter to create and control patches of ionization in the atmosphere at heights around 60 or 80 kilometers. Such ionized patches can reflect electromagnetic signals back toward earth and therefore can act as an artificial "mirror" to reflect OTH radar signals. The AIMS-LO concept is revolutionary because it envisions seizing control of the atmosphere and re-shaping it to create capabilities that are not possible with conventional OTH radars that are constrained by the limitations and vagaries of the natural ionosphere. Among those capabilities are:

- Optimum detection of low-observable targets, including cruise missiles;
- Avoidance of auroral degradation in Northern latitudes;
- Single-site coverage of theaters or cities;
- Detecting and locating missiles, like SCUD, from mobile launchers;
- Suppression of sea clutter, which greatly limits radar performance over oceans.
- Filling the 100-to-1200 kilometers range gap between conventional LOS radars and OTH radars;

The Air Force Geophysics Laboratory (now Phillips Laboratory) initiated research on the feasibility of AIMS-LO in 1987 with support from the Air Force's Electronic Systems Division. Theoretical modeling, laboratory chamber measurements, and numerical simulations were performed by private contractors, universities, and government laboratories associated with the Department of Energy and the Navy. In 1989, the blue-ribbon JASON panel, composed of world-class physicists, reviewed the research results available at that time. That panel's main conclusion was: ". . . We have found no basic physics issues which preclude a realization of . . . [the AIMS-LO] . . .vision." JASON did identify some scientific aspects that required further development, however, and an experimental breakdown facility would contribute to that development.

THE AIMS-LO RADAR VS. CONVENTIONAL RADARS

In order to highlight the potential advantages of AIMS-LO, it is necessary to first describe some basic elements of OTH radars. Such radars depend upon the ionosphere, which bends the radar signals so they return to earth in regions far beyond the horizon formed by the curvature of the earth, hence the name, over-the-horizon radar. An object within the radar beam will scatter some of the signal back toward the receiver and be subject to detection.

It is desirable to match the radar wavelength to the dimension of the target because a resonance occurs that maximizes backward scattered signals. However, the ionosphere imposes constraints on the wavelength chosen for the radar. If the frequency of the radar signal is too high or, equivalently, if the wavelength is too short, the normal ionosphere cannot bend the beam back toward the earth. The practical, lower-limit on wavelength is about 15 meters. Shorter waves penetrate the ionosphere and travel uselessly toward outer space. Although well matched to most airplanes, the 15-to-60 meter usable wavelengths are too long to resonate with small targets, such as cruise missiles or SCUDS.

Beams from north-looking radars encounter the auroral ionosphere, which fluctuates and causes clutter. Such auroral clutter can mask the signals reflected from valid targets. Most such clutter originates at ionospheric heights above 100 kilometers.

Conventional OTH radar signals are reflected from heights of 200-to-300 kilometers in the ionosphere. If the launch angle of the beam is too steep, the signal tends to hit the target on top instead of in the front. This tendency degrades performance. Because steep launch angles correspond to shorter ranges, conventional OTH radars do not work well for ranges shorter than about 1000 kilometers. Conversely, standard LOS radars cannot see beyond the horizon, typically less than 300 kilometers and often less than 150 kilometers.

Sea clutter is the main source of interference for targets over the ocean, such as submarine launched cruise missiles. Sea clutter is substantially lower for horizontally polarized beams than for vertically polarized beams. Unfortunately, Faraday rotation in the normal ionosphere changes the polarization of the radar beam by amounts that are neither predictable nor controllable, so it is not possible to ensure horizontal polarization throughout the path traversed by the radar signal. Conventional radars cannot. therefore, suppress sea clutter by controlling polarization.

Figure 2 illustrated the phenomenon on which the AIMS-LO concept is based. The ionized cloud reflects radar signals so that they return to earth beyond the normal LOS and thus detect targets over the horizon, much like the OTH backscatter radar discussed above. This cloud, called the "artificial ionospheric mirror" (AIM), acts like a small patch of man-made ionosphere. Figures 6-8 (below) illustrate how AIMS-LO can be implemented to augment or replace conventional OTH radars.

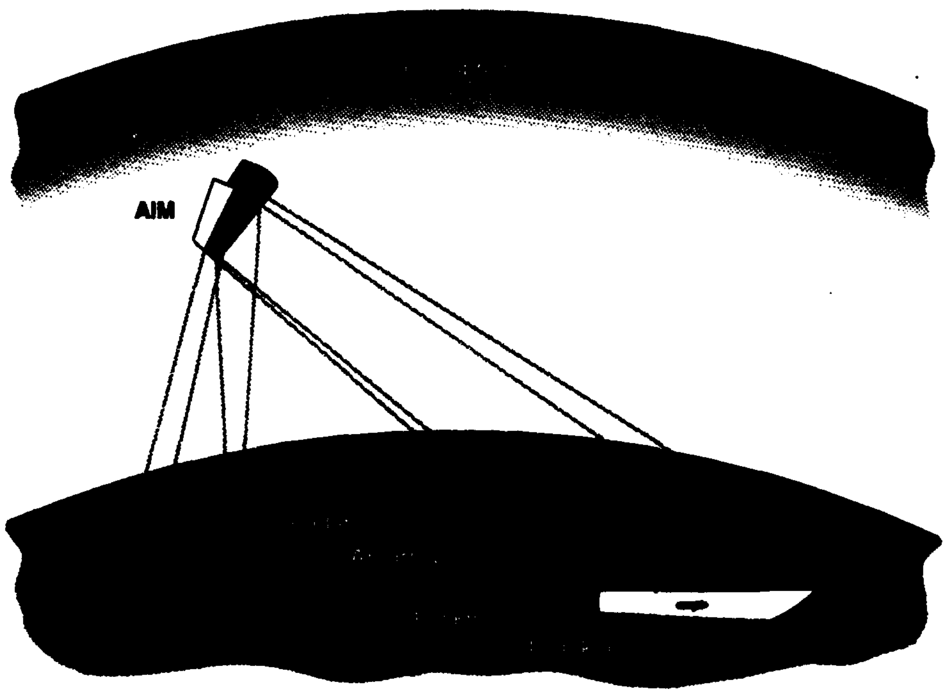

Figure 6. Diagram of how an artificially ionized cloud can be located and oriented for AIMS-LO to cover specified regions.

Why might an AIM cloud be better than the natural ionosphere for the OTH radar application? The answer lies in the fact that the AIM cloud can be controlled, whereas the natural ionosphere cannot. There are, in fact, four aspects of AIMS-LO that relax the four limitations imposed by the ionosphere on conventional OTH radars.

- The density of free electrons in the cloud can be much greater than in the natural ionosphere, and it will therefore reflect signals that have wavelengths as short as 5 meters. This ability to use shorter radar wavelengths can increase the detectability of a small missile by at least tenfold and perhaps a hundredfold.
- Because the cloud can be formed well below the normal ionosphere, radar signals reflected therefrom can fill the important 100-to-1200 kilometers range-gap between the coverage by LOS radars and conventional OTH radars.
- For the reason just cited, the AIM cloud will reflect signals well below heights at which auroras occur, thereby avoiding auroral clutter.
- With the AIM cloud, it is possible to maintain horizontal polarization of the radar beam. This capability reduces interference from sea clutter by around a hundredfold relative to conventional OTH radars.

The combined improvements afforded by using shorter wavelengths and horizontal polarization enormously complicates an adversary's task in fabricating low-observable targets. In addition, by controlling the height and orientation of the mirror, it is possible to point the radar beam in various directions, thereby accomplishing 360 degree coverage from a single site.

Note that Fig. 6 is color coded to show how various mirror orientations can be used to point the AIMS-LO beam to regions not accessible with beams that reflect from the normal ionosphere. Such pointing gives multi-directional coverage from a single site. Figure 7 shows how AIMS-LO can be configured in a theater (or city) defense mode against aircraft or mobile launched missiles, like SCUD. Figure 8 illustrates the AIMS-

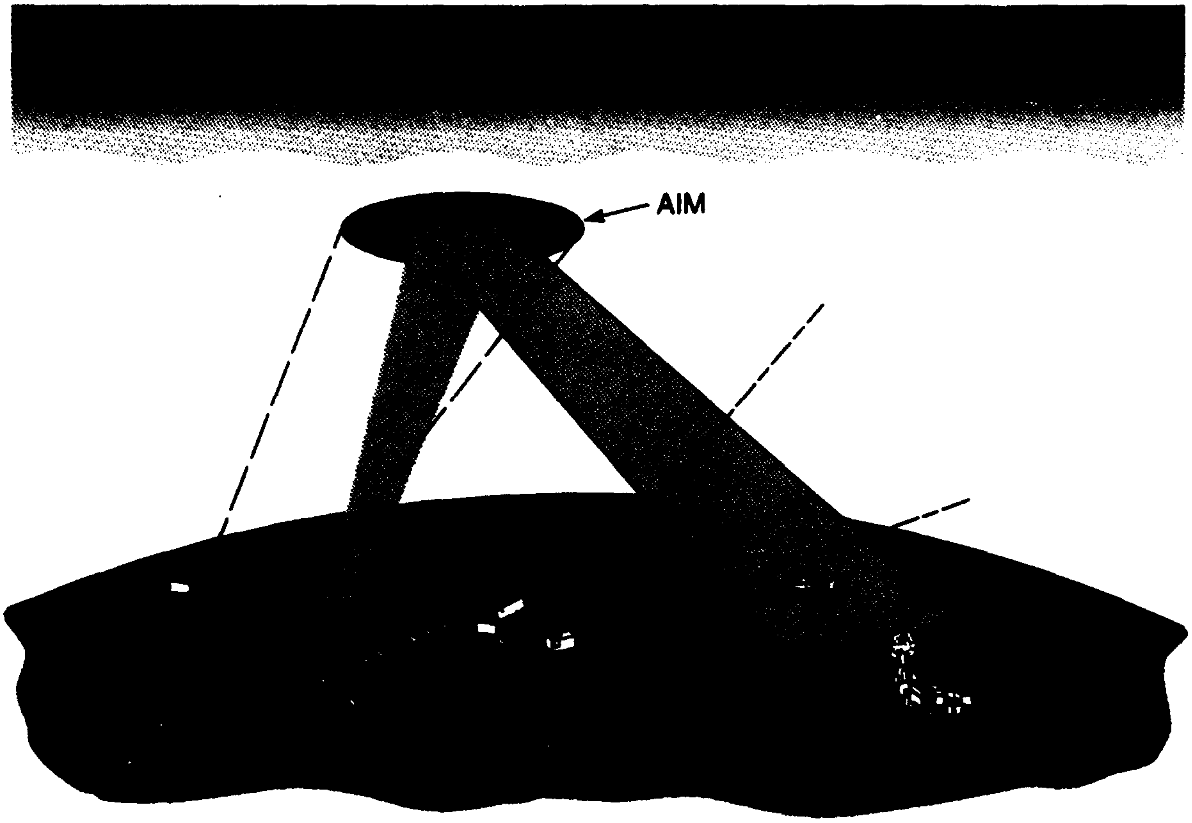

Figure 7. Example of AIMS-LO radar deployment for theater coverage against tactical aircraft or missiles from mobile launchers.

LO capability for broad area surveillance--in this case, the Mideast--for defending global interests.

SCIENTIFIC ISSUES FOR AIMS-LO

The AIMS-LO array might at first glance seem to be little more than the experimental breakdown facility described in Sec. 2. Indeed, both AIMS-LO and the breakdown facility involve powerful transmitters and large antennas or arrays capable of delivering electric fields strong enough to produce breakdown in the upper atmosphere without also producing unwanted breakdown near the transmitter in the lower

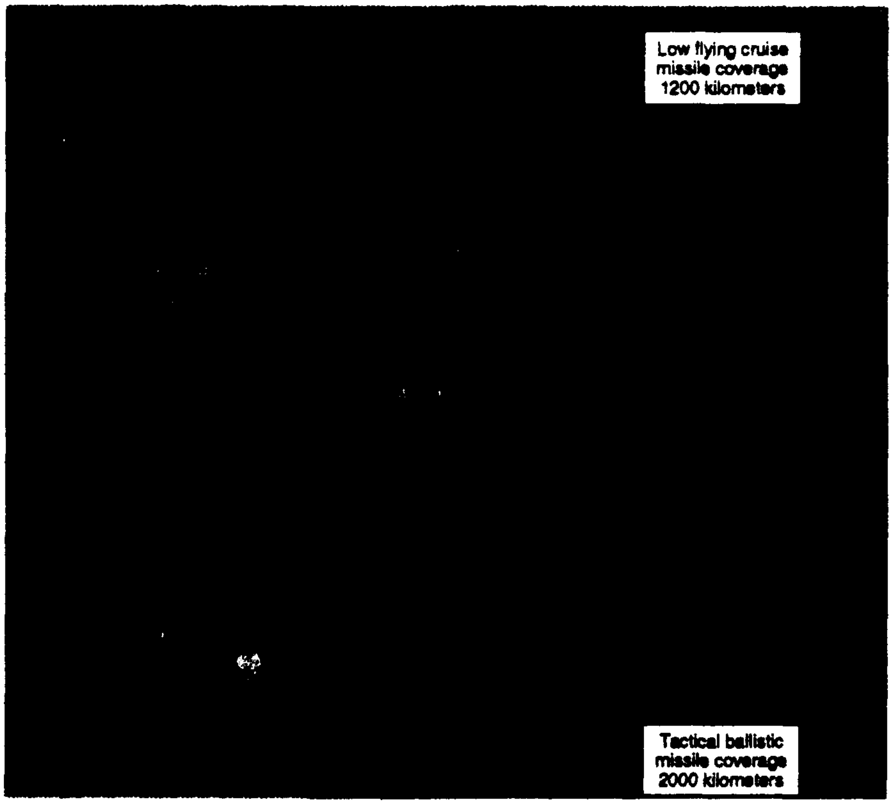

Figure 8. AIMS-LO broad area surveillance for defending global interests.

atmosphere. However, the requirements for an operational AIMS-LO array are more stringent than the experimental breakdown facility.

Whereas the breakdown facility must produce enough ionization and emissions to be detectable and measurable, AIMS-LO must go farther. It must produce enough ionization to reflect radar signals whose wavelengths are as short as a few meters. The cloud must have relatively sharp edges; otherwise it will be a "mushy" mirror that absorbs rather than reflects the radar signal. The cloud must be uniform rather than lumpy, otherwise the reflected signal will be scattered in unwanted directions. The cloud must be large--perhaps a kilometer on a side--and properly oriented. Once established, it must persist for a substantial fraction of a second; otherwise there will not be time to scan the array beam over other spots and paint a mirror of useful size. And there will not be adequate dwell time for a radar application. The AIM cloud must not fluctuate in a way that introduces "jitter" into the radar signal which can interfere with the target signature.

The above requirements imply that several scientific issues and trade-offs must be resolved before operational deployment. One such issue is the choice of the optimum height at which to form the cloud. If the height is too low, the cloud will not persist long enough because the free electrons quickly attach to the abundant air molecules and so-called collisional losses cause the cloud's reflectivity to be inadequate. If the cloud is too high, on the other hand, diffusion, turbulence and other processes that occur in rarefied gases can alter its structure. Studies to date indicate that 70-to-100 kilometers is the preferred height range for the AIMS-LO cloud, but data gathered with a breakdown facility will be useful for selecting the best height.

The quality and uniformity of the AIMS-LO cloud depends upon the uniformity of the array beam as well as a number of atmospheric processes, especially wind shears, diffusion, and so-called plasma instabilities in the cloud. The breakdown facility, along with associated diagnostics, will help provide data needed to predict the uniformity of the cloud. Moreover, the breakdown facility will provide an ionization patch, perhaps a modest one, that can be used for experiments on how irregularities affect the quality of communication or radar signals reflected from the patch. It will also provide much needed data on the efficiency with which high-power radio frequency energy is converted to ionization at various heights in the atmosphere.

Section 6

RELIABLE COMMUNICATION LINKS

Prior sections of this paper have shown that an artificial ionospheric mirror acts like a pointable, passive, low-altitude communications satellite. Such a mirror might (1) reflect very-short-wave signals that ordinarily would pass uselessly through the ionosphere and into space; (2) be located and oriented to direct signals toward specified locations while avoiding undesired locations; and (3) reflect signals below the ionosphere, thereby avoiding degradation from ionospheric fluctuations. Section 5 described the virtues of these properties for radar applications. An artificial ionospheric mirror can also help to create communications links that are free from the vagaries of the natural ionosphere.

Because of fluctuations in the ionosphere, periods occur when HF propagation conditions are poor and successful transmission difficult. In such cases, the carrier frequency must be changed from time to time, and outages occur. Polar regions are especially troublesome in this regard because of auroral effects. The ability to control the ionosphere and cause radio wave reflection below the aurora would allow predictable HF communications at predetermined frequencies. Frequencies higher than the HF band might also be used.

Several suggestions have been made from time to time that the artificial ionospheric mirror could be used to support special purpose military communications. Because the artificial mirror supports radio frequencies and paths not available to an adversary, it might be used to establish secure communication links that can neither be jammed nor intercepted. It has even been suggested that AIM's ability to reflect short waves from heights below ionospheric disturbances could be used to avoid blackout in nuclear environments. Although such applications are scientifically feasible, their practicality cannot be proven until the appropriate scenarios have been analyzed in depth. Such scenario analysis is beyond the scope of this paper.

Section 7

NON-NUCLEAR SIMULATION AND MODELING OF HIGH-ALTITUDE NUCLEAR EFFECTS (HANE) ON SURVEILLANCE SYSTEMS

Although dissolution of the Soviet Union has greatly reduced the chance that high altitude nuclear detonations will ever occur, it is worth noting that a breakdown facility has a capability for non-nuclear simulation of nuclear events. It is beyond the scope of this paper to assess the future likelihood of high altitude nuclear explosions, but laws of physics apply regardless of political change.

The atmosphere responds to a high-altitude nuclear detonation in many ways, all of which degrade the performance of current and contemplated military systems. A nuclear detonation ionizes and excites air molecules over a huge volume. Those molecules radiate much of their radiation energy in optical bands. That radiation can damage or overwhelm optical surveillance systems. In addition, a high-altitude nuclear burst causes many other effects, including: plasma instabilities, field-aligned irregularities, shock and gravity waves, and disruption of electromagnetic wave propagation. Figure 9 is a photograph of a high-altitude nuclear explosion which shows several of the effects just mentioned, particularly optical emissions. An atmospheric breakdown facility offers a unique opportunity to simulate realistically certain effects of high-altitude nuclear weapons on existing or planned military systems, especially surveillance systems.

The DNA and other DOD agencies have supported research to determine the response of the upper atmosphere to high-altitude nuclear explosions. The goal is to understand the physical and chemical parameters and, hence, predict and mitigate the degradation to military system performance. Despite many years of effort, however, important issues remain unresolved. The main hurdle is that nuclear weapons deposit

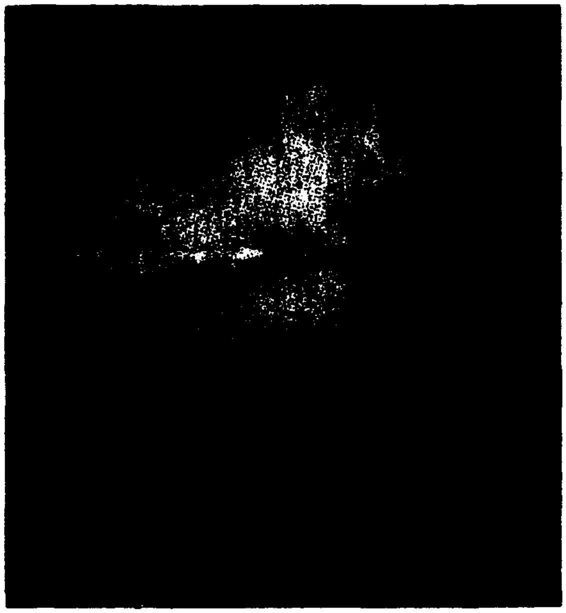

Figure 9. The Hardtack Orange nuclear explosion as photographed from sea level about 1 minute after detonation. Orange was a megaton-range weapon detonated at an altitude of about 45 kilometers.

such an enormous amount of energy into the atmosphere that accurate non-nuclear simulation of the environment has been impossible.

In the past, absence of atmospheric nuclear testing has confined simulation of the nuclear environment to the laboratory by use of large vacuum ionization chambers with sophisticated radiation sources and diagnostic devices. Many useful results have been obtained, but questions were raised by the limited size of such chambers and the unwanted effects caused by chamber walls.

In order to avoid the spatial constraints imposed by laboratory chambers, measurements have been made of the atmosphere during naturally occurring events that deposit energy at altitudes above 30 kilometers. Such experiments have included ground-, rocket-, and satellite-based measurements during auroras, strong solar flares, and solar proton events, all of which vaguely mimic high-altitude nuclear explosions. The resulting data have given valuable insight into the natural atmosphere and have helped develop models of the nuclear-disturbed ionosphere. Those data suffer from two limitations, however, because the energy deposited in the atmosphere during natural events is (1) uncontrolled and therefore poorly understood, or (2) orders of magnitude less intense than the energy deposited by a nuclear weapon. A breakdown facility offers the promise of removing both shortcomings; the energy deposited is controlled and very intense, albeit over a limited volume.

The following discussion deals with how a breakdown facility can help to understand and mitigate nuclear degradation.

OPTICAL EFFECTS OF HIGH-ALTITUDE NUCLEAR DETONATIONS

A nuclear detonation will deposit energy into the atmosphere via X-rays, gamma rays, beta rays, neutrons, and kinetic energy of fast moving bomb debris. That energy will alter the atmosphere's composition over hundreds to thousands of kilometers and drive chemical processes that never occur under natural conditions. Many of these processes are photochemical, which means that they emit radiation over the entire optical spectrum: ultraviolet, visible, and infrared. Much of that radiation is emitted in the passbands used by surveillance, detection, tracking, and homing systems. Moreover, the deposited energy disrupts the natural atmospheric optical windows or absorption bands on which systems are designed to depend. The effects persist for long periods of time, during which they blind or deny valid signals to optical sensors.

The following is an abridged list of nuclear-weapon induced optical emissions that could degrade system performance:

- Non-equilibrium production of nitric oxide, which radiates strongly in the short- and medium-wavelength infrared (SWIR and MWIR) bands used by most surveillance systems, as well as in the long-wavelength infrared (LWIR) band used for detection and discrimination of warm-body re-entry vehicles.

- Widespread and possibly strong infrared radiation from atomic oxygen which could interfere with tracking of tactical missiles, such as SCUD, as well as re-entry vehicles.
- Visible and ultraviolet radiation from hot incandescent air, principally nitrogen and oxygen molecules, which can interfere with detectors that home on short-to-medium range missiles.

All of the above optical radiations, and others, can be produced and controlled over a range of heights by a breakdown facility. By monitoring the spectral content, intensity, and decay of that radiation, a much better understanding of the physics can be obtained, and that knowledge can be used to formulate improved models of system performance in nuclear environments.

Another important systems related process that could be evaluated with the aid of a breakdown facility is the structure or "mottling" that occurs in the infrared emissions from photochemical processes driven by the X-ray impulse from a high-altitude nuclear explosion. Although the radiation itself is a nuclear effect, its spatial structure is governed by the structure of the normal or aurorally disturbed atmosphere just prior to the detonation; in effect, the X-rays impress the radiation onto the preexisting structure. The issue is an important one because it is this structure that produces clutter which reduces the signal-to-noise ratio in optical signals to below useful thresholds.

The upper atmosphere's structure has heretofore not been amenable to adequate experimental determination, but the breakdown facility offers the opportunity to investigate structured infrared emissions. By depositing energy smoothly at heights of 70-to-100 kilometers, where most weapon X-rays would be deposited, the facility would produce emissions whose spatial structure can be sensed remotely. Moreover, the beam from the facility could be used to paint that part of the atmosphere with a pattern optimized to interfere with infrared detection systems, and the ability of those systems to deal with such clutter could be tested.

Besides giving insight into degradation by nuclear effects, such an experiment would show whether an attacker could use its own breakdown facility to mask the boost phase of missile launches. Specifically, by painting an optimized infrared radiating structure above its launch site, an attacker might present boost phase detection systems with great difficulty in detecting missile launches or providing a missile track for handover to homing and intercept system elements. This type of launch masking could be accomplished without resorting to a nuclear precursor.

Section 8

RESEARCH IN THE FORMER SOVIET UNION AND COLLABORATION WITH THE COMMONWEALTH OF INDEPENDENT STATES (CIS)

The former Soviet Union conducted an orderly and innovative research program on atmospheric breakdown, combining theoretical studies, numerical modeling, laboratory observations, and atmospheric experiments. The concept of using dual, intersecting high-power microwave beams to define and sustain an ionized region originated in the former Soviet Union. Achieving steady progress over the past decade, they developed a well-defined recommendation for a prototype facility using a multiple-pulse intersecting beam method of ionizing the neutral atmosphere. That approach, leading to artificially ionized radio reflectors, has been described in the Soviet literature as offering new paths for a wide variety of civilian and military RF applications, including enhanced long-range communications and avoidance of disturbed environments. A decision to proceed with facility development in the CIS has not yet been made.

Opportunities for cooperative research studies with the CIS in this area appear realistic, with a joint symposium on artificial ionization research having been held as part of the International Workshop on Nonlinear and Turbulent Processes in Physics, Kiev, October, 1989. Another meeting was held in the USSR during the International Workshop on Strong Microwaves in Plasmas, in September, 1990. As a result, several inquiries regarding U.S.-CIS cooperation have been received from leading CIS scientists, including Academicians Gurevich, Galeev, and Sagdeev (former head of Soviet Space program). A specific example of U.S.-CIS cooperation is the East-West Technology Center (under Sagdeev's direction) formed at the University of Maryland to foster scientific exchanges between the U.S. and eastern countries, the former Soviet Union in particular.